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ANOMALOUS EVOLUTION OF THE DWARF GALAXY HIPASS J1321-31[1]

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ABSTRACT

We present HST/WFPC2 observations of the dwarf galaxy HIPASS J1321-31. This unusual galaxy lies in the direction of the Centaurus A group of galaxies, and has a color-magnitude diagram with a distinctive red plume of luminous stars. This feature could arise from (a) a red giant branch if the galaxy were much nearer than previously recognized, (b) a peculiar asymptotic giant branch, or, (c) an ~ 1 Gigayear old population of intermediate mass red supergiants, which we find to be the most likely explanation. However, the lack of equally luminous blue stars requires that the star formation has dropped substantially since these stars were formed. Evidently HIPASS J1321-31 experienced an episode of enhanced star formation rather recently in its star formation history followed by a period of relative quiescence which has led to the evolution of the main sequence stars into the red supergiant branch. The stellar populations in HIPASS J1321-31 reflect a star formation history that is uncommon in star forming dwarf galaxies. This is the first time such a star formation history has been noted, although the literature contains a small number of other dwarf galaxies with similar color-magnitude diagrams. Therefore, HIPASS J1321-31 and these other galaxies represent a different path of dwarf galaxy evolution that has not been well-explored and an important probe into how dwarf galaxies evolve.

Subject headings: galaxies: dwarf—galaxies: individual (HIPASS J1321-31)—galaxies: stellar content

1. INTRODUCTION

Dwarf galaxies are the most common type of galaxy in the Universe. In cosmological models, such as those invoking cold dark matter, the first and most frequently formed gravitationally bound objects resemble present-day dwarfs. Many studies have been made of these galaxies, allowing us a glimpse into the conditions and evolution of galaxies in the youthful Universe. While the stellar populations of dwarf galaxies in the Local Group have been extensively investigated (see Mateo 1998 and references within; Grebel 1997), this represents only one environment in which these types of galaxies are known to exist. Still open is the question of how, and if, dwarf galaxies evolve from initial gas clouds to dwarf irregular galaxies to dwarf spheroidal galaxies (e.g., Grebel, Gallagher, & Harbeck 2003). Furthermore, we need to establish whether dwarf galaxies outside the Local Group have similar relationships between star formation histories and other global and environmental properties.

Numerous studies have explored the global properties of dwarf galaxies in nearby galaxy groups and clusters. However, detailed investigations of star formation histories derived from resolved stellar populations are limited to the nearest galaxy groups, which require the capabilities of the *Hubble Space Telescope* (HST). Thus we now have Wide-Field Planetary Camera 2 (WFPC2) color-magnitude diagrams (CMDs) for significant samples of dwarf galaxies in the M81 (e.g., Karachentsev et al. 2002a) and the Centaurus A (Cen A; Karachentsev et al. 2002b) groups. These and similar data suggest diverse star formation histories among nearby dwarfs, similar to those found in the Local Group. Dwarf spheroidal and transition galaxies show dominant red giant branches (RGBs), while the luminous stellar populations in irregulars consist of a mixture of the RGB stars along with more massive stars and their evolved descendants. Galaxies where the old RGB is weak are rare, but this condition is seen in the dwarf irregular galaxies Leo A (Tolstoy et al. 1998; Schulte-Ladbeck et al. 2002) and Holmberg IX (Karachentsev et al. 2002a; Marakova et al. 2002). This suggests that larger samples of resolved dwarf galaxies will reveal rarer or shorter lived evolutionary paths.

One property that makes the dwarf galaxies in Cen A interesting to study is the fact that so many of them are gas-rich. No dwarfs in the Local Group are young in the sense that they still contain more mass in gas than in stars. However, some of those that have been found in a blind HI survey of the nearby Cen A group are (HI Parkes All-Sky Survey [HIPASS]; Banks et al. 1999). After a number of new candidate dwarf galaxies were discovered, we undertook follow-up observations of a select number of them using the HST/WFPC2, giving us the opportunity to study the resolved stellar populations and thus the evolutionary histories in gas-rich Cen A group dwarfs. In this letter we discuss the unusual nature of one of these systems, HIPASS J1321-31. In a future paper we discuss its physical properties along with the other Cen A dwarfs observed is this program, HIPASS J1337-39 and HIDEEP J1337-33 (Grossi et al. 2003). We find that the color-magnitude diagram (CMD) of HIPASS J1321-31 shows a significantly different stellar population from the other two dwarf galaxies surveyed, as well

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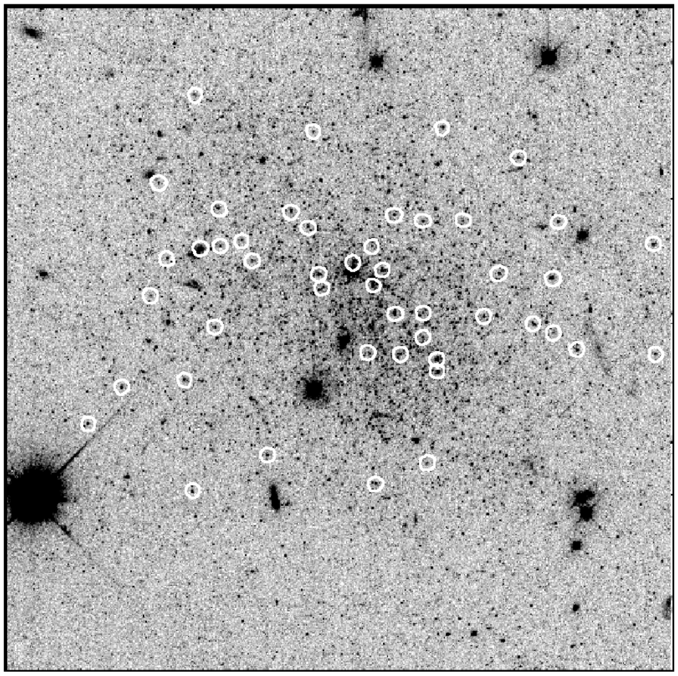

FIG. 1.— Image of HIPASS J1321-31 from the WFC3 showing its well-resolved stellar population. The circles indicate the stars that belong to the red plume seen in Figure 2a.

as most Local Group dwarfs. In the following we present the CMD of HIPASS J1321-31 and discuss the possible origins of its "unique" stellar populations.

2. OBSERVATIONS AND REDUCTIONS

HIPASS J1321-31 was observed with the WFPC2 on 2001 June 12 with four exposures in F555W at 1200 sec each and four exposures in F814W at 1300 sec each, with the galaxy centered on the WFC3 (Figure 1). The images for each filter and chip were combined to create a deeper image of the galaxy. DAOPHOT, ALLSTAR, and ALLFRAME were used to obtain the profile-fitted photometry of the stars presented in this letter. The point spread functions (PSFs) used in the reductions were kindly communicated to us by P. B. Stetson (see Stetson et al. 1998). Due to the lack of stars on the PC, we chose not to reduce that chip. Limits in χ ($\chi > 2.0$) and sharpness ($-0.1 <$ sharp < 0.1) were placed on the fits of the stars to remove any objects with questionable photometry. CTE corrections were made using the equations from Whitmore, Heyer, & Casertano (1999). After the aperture corrections were calculated from the unsaturated brightest stars in each chip, the photometry was calibrated to the standard V and I system using the equations in Holtzman et al. (1995).

To check the reliability of the photometry and confirm that the red plume apparent in the CMD was "real," the data were also reduced using DoPHOT and independently using DAOPHOT/ALLSTAR with different PSFs. In both cases, the red plume was still present. We also checked the location of the red plume stars against any defects in the WFC3, such as warm pixels, and found the photometry was unaffected by these difficulties.

3. COLOR-MAGNITUDE DIAGRAM

Figure 2a shows the CMD for the WFC3, which was centered on HIPASS J1321-31. The CMD for the field (WFC2 and WFC4) is seen in Figure 2b. Figure 2a shows a clear red plume of luminous stars. These stars are scattered across the optical extent of the galaxy (see Figure 1). We know that HIPASS J1321-31 has a heliocentric velocity of 572 km/s according to the HI survey of Banks et al. (1999). This is consistent with it being a member of the Cen A Group and proves to be important in interpreting the CMD. In the following we discuss three possible interpretations for the red plume: A RGB, an asymptotic giant branch (AGB), or a red supergiant branch (RSGB).

3.1. *The Red Plume*

One might think that the red plume seen in Figure 2a is the RGB of HIPASS J1321-31. Assuming this to be true, the tip of the red giant branch (TRGB) would be at $m_I \sim 22.6$ mag. In this case using this value for the TRGB, we estimate the distance to the galaxy to be about 2.0 Mpc, assuming $M_{I,\mathrm{TRGB}} = -4.05$ (Da Costa & Armandroff 1990) and $E(B{-}V) = 0.062 \pm 0.01$ (Schlegel, Finkbeiner, & Davis 1998). This estimate places HIPASS J1321-31 just outside the Local Group in the direction of the Cen A group of galaxies. The distance to the giant elliptical galaxy Cen A is 3.9 ± 0.3 Mpc (Harris, Harris, & Poole 1999), but HIPASS J1321-31 is located closer in the sky to M83, which has a distance of 4.5 ± 0.3 Mpc (Thim et al. 2003). This interpretation would place HIPASS J1321-31 somewhere between the Milky Way and M83. This is in conflict with the radial velocity found for the HI cloud associated with the galaxy, which is consistent with it being a member of the more distant Cen A group. This apparent conflict could be resolved if the HI cloud were not associated with the stellar galaxy, but such a chance coincidence would be unique and is highly unlikely.

However, the biggest challenge to the RGB interpretation is the fact that the red plume is not well populated even well below its tip. For globular clusters and dwarf galaxies, the number of stars increases as one moves fainter along the RGB. Figure 3

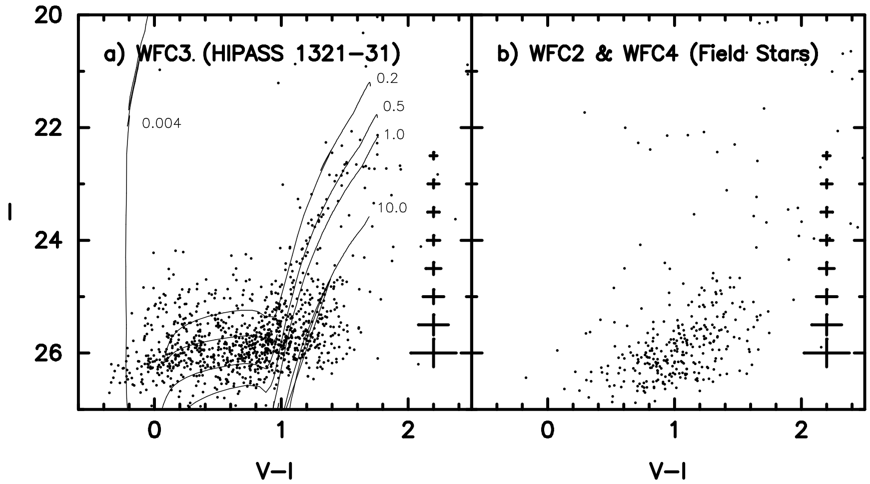

FIG. 2.— Color-magnitude diagrams for (a) the WFC3 which shows HIPASS J1321-31 and (b) the field surrounding the galaxy from the WFC2 and WFC4. A comparison of the two plots shows that HIPASS J1321-31 contains a population of blue stars and a red plume of stars. Padova theoretical isochrones (Girardi et al. 2002) are shown for $Z = 0.0004$, where the ages listed are in Gyr. In this case, the best fit to the red supergiant branch is 0.5 Gyr. Isochrones showing the young (0.004 Gyr) and old (10 Gyr) tracks are for illustrative purposes.

shows the luminosity function for HIPASS J1321-31. The luminosity function has been Gaussian-smoothed using Eq. A1 in Sakai, Madore, & Freedman (1996). In the magnitude range from $24.0 < m_I < 22.0$, the luminosity function is relatively flat. We used the data in Saviane, Held & Piotto (1996) to create a luminosity function for the RGB in Tucana (the dashed line in Figure 3). The tip of the Tucana RGB was shifted to match the tip of the red plume in HIPASS J1321-31 and was scaled so that the upper luminosity functions are reasonably well-matched. The relatively constant luminosity function of the HIPASS J1321-31 red plume is in contrast to the increasing luminosity function of the Tucana RGB. The combination of distance difficulties and flat luminosity function argue that the red plume is not a RGB.

A second possibility is that the red plume is an AGB. A strong AGB population is seen in dwarf galaxies like IC 1613 (Cole et al. 1999) and Sextans A (Dohm-Palmer et al. 2002). In these galaxies, the AGB extends around 0.5 mag in I above the TRGB and then turns redward. This differs from the behavior of the red plume in HIPASS J1321-31. It extends at least two magnitudes above any possible TRGB and begins its assent from the bluer part of the possible RGB. Thus, it is implausible that the red plume consists of AGB stars.

Ruling out the RGB and AGB leaves us with the likelihood that these stars make up the RSGB. Such stars originate from intermediate mass stars in post-main sequence helium core burning evolutionary phase, the same phases that produce pronounced "blue loops" at low metallicities. A beautiful example of this phenomenon is seen in Sextans A, where stars with ages of < 1 Gyr mark the red and blue edges of loop evolution (Dohm-Palmer et al. 1997). However, for cases where the evolved stars have ages near 1 Gyr the red branch of the evolutionary loop dominates (see Fig. 3 of Dohm-Palmer et al.). Thus in this model HIPASS J1321-31 would be in something resembling a post burst phase where the star formation rate was enhanced ≤ 1 Gyr in the past, giving rise to an unusual number of evolved stars with initial masses slightly less than 3 $M_\odot$.

We searched the literature for other dwarf galaxies with similar CMDs as HIPASS J1321-31. In the HST snapshot survey of dwarf galaxies (Karachentsev et al. 2002a, b, c; 2003a, b, c) there are several with red plumes similar to HIPASS J1321-31. They are all found to extend from the bluer part of the RGB and trend slightly to the red as one moves to higher luminosity along the branch. We investigated the number of stars along the red plumes in a couple of these galaxies and found that they remain relatively constant, similar to what we see in the luminosity function for HIPASS J1321-31 (see Figure 3). Therefore, as noted by Karachentsev et al., it is likely these red plumes are RSGBs, including the one in HIPASS J1321-31, arising from intermediate mass stars.

We can test the intermediate mass RSG hypothesis by seeing if the presence of a normal RGB is consistent with our data. Following the approach adopted in the Karachentsev et al. papers, we used the edge-detection filter equation in Sakai, Madore, & Freedman (1996) to search for the TRGB. Applying the equation to those stars between $0.8 < V - I < 2.0$ results in an edge being detected at $m_I = 24.65 \pm 0.11$ mag, where the error includes the photometric uncertainty (± 0.06), the uncertainty in the TRGB estimate (± 0.06), the uncertainty of the photometric zeropoint (± 0.05), and the uncertainty in the aperture corrections (± 0.05). This agrees with the visual impression of the point where the luminosity function begins to rise in Figure 3, and is a clear signature of the beginning of the RGB. Assuming the TRGB to be at $M_I = -4.05$ (Da Costa & Armandroff 1990), $E(B-V) = 0.062 \pm 0.01$ (Schlegel, Finkbeiner, & Davis 1998), and $R_V = 3.1$, the distance modulus estimated from the TRGB is $(m - M)_0 = 28.59 \pm 0.13$. The distance to HIPASS J1321-31 is thus 5.2 ± 0.3 Mpc. This would place the galaxy beyond M83, but it would still be a member of the Cen A group, in good agreement with the heliocentric velocity of the HI cloud.

4. WHAT DOES THIS MEAN?

What are the astrophysical implications of such a pronounced RSGB in HIPASS J1321-31 and other dwarfs? The difficulty in understanding the RSGB in HIPASS J1321-31 is the apparent deficiency of corresponding BSGB stars. Dwarf galaxies such as Sextans A, IC 1613, and those observed in the HST snapshot survey for dwarf galaxies, all exhibit a strong population of blue stars reaching nearly as high as the RSGB. These blue stars are made up of an uncertain combination of upper main sequence and evolved intermediate mass stars with ages < 300 Myr. The

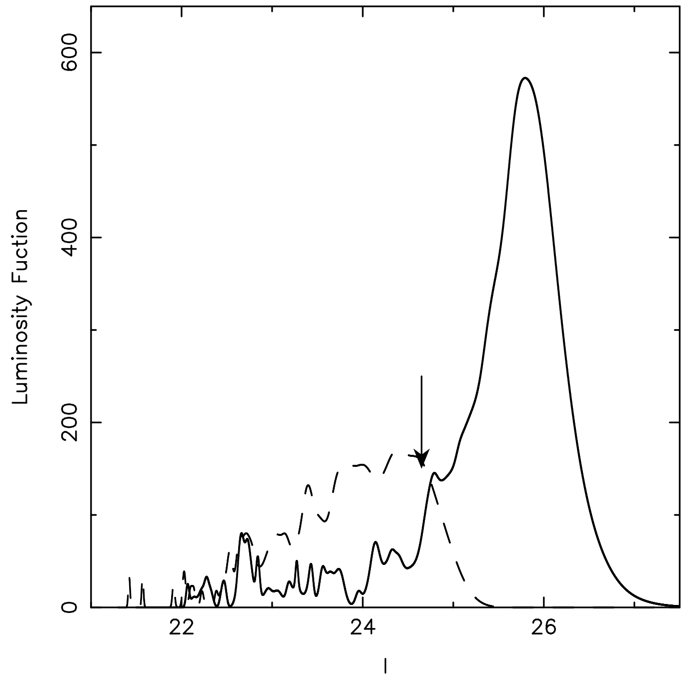

FIG. 3.— Luminosity function of the HIPASS J1321-31 stars within $0.8 < V - I < 2.0$ as shown by the solid line. It has been Gaussian-smoothed using Eq. A1 in Sakai, Madore, & Freedman (1996). The dashed line represents the luminosity function of the Tucana dwarf galaxy's red giant branch. The tip of the Tucana red giant branch was shifted to match the tip of the red plume in HIPASS J1321-31. This illustrates the constant luminosity function of the red plumes, in contrast to the increasing luminosity function of a red giant branch. The arrow indicates the location of the tip of the red giant branch in HIPASS J1321-31.

comparable luminosity of the red and blue plume in Sextans A and IC 1613 then reflects relatively high levels of ongoing star formation. The absence of bright blue stars in HIPASS J1321-31 cannot be due to observational problems, for we see them in the HST data of the other HIPASS dwarf galaxies (Grossi et al. 2003).

One possible scenario is that HIPASS J1321-31 experienced an episode of enhanced star formation, and possibly a mild starburst, less than a Gyr ago when the stars now populating the RSGB were formed. Using the Bertelli et al. (1994) and Girardi et al. (2002) isochrones, we found that evolved stars with masses around 2-3 $M_{\odot}$ and low metallicities on the red branch of the core-helium burning phase would be dominant, while the corresponding blue loop stars would be too faint to be detected in our observations. The presence of the faint blue hump implies that star formation continued for a few hundred million years at a lower rate. Figure 2a shows a number of theoretical isochrones (Girardi et al. 2002) for $Z = 0.0004$. While this gives some idea of the age range of the RSGB, more detailed modeling will be discussed in Grossi et al. (2003). In addition to an absence of luminous blue plume stars, we did not find any HII regions in narrow-band Hα images taken with the WIYN telescope. HIPASS J1321-31 has a high amount of gas in it ($M_{HI}/L_B = 5.0$; Table 1). If it did experience a significant burst of star formation in its past, this could have spurred further star formation throughout the galaxy. Yet, there is no evidence of recent or continuous star formation. An interesting question then is not only why the star formation rose in the past but also why it now appears to have fallen?

We find the tip of the RSGB to be around $m_I = 22.6$ mag yielding an absolute magnitude of $M_I = -6.1$ mag assuming $M_I = -4.05$ for the TRGB. The Karachentsev et al. (2002a, b, c; 2003a, b, c) galaxies with well-populated normal RSGBs have tips from $M_I = -7.0$ up to -8.7. So the faintest RSGB tip in these other galaxies is still about one magnitude brighter than that for HIPASS J1321-31. This suggests that its RSGB derives from an older stellar population since the younger stars which would populate the brighter end of the RSGB are gone, i.e., evolved away, and the corresponding BSGB stars are missing as well. Therefore, HIPASS J1321-31 shows a star formation history that is uncommon in known dwarf galaxies.

Searching through the Karachentsev et al. (2002a, b, c; 2003a, b, c) papers, we have found only two galaxies with similar CMDs to HIPASS J1321-31 whose observed properties we list in Table 1. None of the Local Group dwarfs have this feature in their CMDs. ESO 444-G084 (Karachentsev et al. 2002b), another galaxy in the Cen A group, shows a possible RSGB which is less populated than the one in HIPASS J1321-31, along with a fainter population of blue stars. Another nearby dwarf galaxy KK 65 (Karachentsev et al. 2003a) has a CMD with what looks to be a dispersed RSGB. A faint population of blue stars can also be seen, but the difference between the tip of the RSGB and the blue plume is not as great as that in HIPASS J1321-31. From Table 1 we can see that each of these galaxies are gas-rich, but HIPASS J1321-31 stands apart due to its low luminosity. Another dwarf galaxy, UGC 8833, found in the Canes Venatici I cloud has a similar blue plume and RGB to HIPASS J1321-31, but it lacks a RSGB (Karachentsev et al. 2003b). The physical properties of these two galaxies are similar, except that HIPASS J1321-31 has a much higher HI mass-to-light ratio (see Table 1). This comparison helps illustrate that HIPASS J1321-31 must have had a period of increased star formation in its rather recent past in order to create its RSGB.

5. SUMMARY & CONCLUSIONS

We present the CMD for the gas-rich dwarf galaxy HIPASS J1321-31 as observed by the HST/WFPC2. A bright red plume of stars along with a much fainter (~ 2 mag) pop-

ulation of blue stars indicate that the galaxy has experienced a peculiar star formation history. Three explanations for this red plume were discussed. We rule out the possibilities of it being a RGB or AGB, and conclude that the red plume is composed of core helium-burning post-main sequence stars with ages $\lesssim 1$ Gyr, possibly as young as 0.4 Gyr. These are likely to be related to an epoch when the galaxy experienced an increase in the star formation rate. This event was not associated with the birth of the galaxy since an older RGB is present — HIPASS J1321-31 is not a young galaxy. Several puzzles remain, such as the source of the possible starburst and how the large gas content and unusual evolutionary history might be linked (e.g., could this dwarf consists of tidal debris? see Marakova et al. 2002).

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TABLE 1
PHYSICAL PROPERTIES OF HIPASS J1321-31 AND COMPARISON DWARF GALAXIES

Galaxy	RA (2000)	Dec (2000)	$v_\odot$ km/s	a $'$	m_B	M_B	$M_{\rm HI}$ $10^7 M_\odot$	$M_{\rm HI}/L_B$
HIPASS J1321-31	13:21:06	–31:32:25	572	1.2	17.1	–11.7	3.7	5.0
ESO 444-G084	13:37:20	–28:02:45	591	4.6	15.1	–13.5	5.6	1.4
KK 65	07:42:32	+16:33:39	554	4.5	15.6	–12.7	1.6	0.9
UGC 8833	13:54:49	+35:50:15	228	0.9	15.2	–12.4	1.3	1.0